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# Off-limb (spicule) DEM distribution from SoHO/SUMER observations

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**Abstract** In the present work we derive a Differential Emission Measure (DEM) distribution from a region dominated by spicules. We use spectral data from the *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER) spectrometer on-board the *Solar Heliospheric Observatory* (SoHO) covering the entire SUMER wavelength range taken off-limb in the Northern polar coronal hole to construct this DEM distribution using the CHIANTI atomic database. This distribution is then used to study the thermal properties of the emission contributing to the 171 Å channel in the *Atmospheric Imaging Assembly* (AIA) on-board the *Solar Dynamics Observatory* (SDO). From our off-limb DEM we found that the radiance in the AIA 171 Å channel is dominated by emission from the Fe IX 171.07 Å line and has sparingly little contribution from other lines. The product of the Fe IX 171.07 Å line contribution function with the off-limb DEM was found to have a maximum at $\log T_{max}$ $(K)$ = 5.8 indicating that during spicule observations the emission in this line comes from plasma at transition region temperatures rather than coronal. For comparison, the same product with a quiet Sun and prominence DEM were found to have a maximum at $\log T_{max}$ $(K)$ = 5.9 and $\log T_{max}$ $(K)$ = 5.7, respectively. We point out that the interpretation of data obtained from the AIA 171 Å filter should be done with foreknowledge of the thermal nature of the observed phenomenon. For example, with an off-limb DEM we find that only 3.6% of the plasma is above a million degrees, whereas using a quiet Sun DEM, this contribution rises to 15%.

**Keywords:** Corona, transition region

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## 1. Introduction

For a long time spicules (Beckers, 1968) have been examined as structures that intermittently couple the chromosphere and the corona through a continuous ejection of mass flux and thereby causing heating. However, the coronal counterparts of these jets were never found (Withbroe, 1983; Mariska, 1992). Thus the idea of their direct contribution to coronal heating was shelved (Withbroe, 1983) until recently. De Pontieu *et al.* (2007) revived this idea when they used off-limb coronal hole data to show that high velocity spicules (so called type II spicules) existing in the solar chromosphere exhibit only upward motions. Rouppe van der Voort *et al.* (2009) correlated the off-limb type II spicules to on-disk Rapid Blueshifted Excursions (RBEs) and established that these features occur ubiquitously on the Sun. Their disappearance from the Ca II H passband images taken with the *Solar Optical Telescope* (SOT) on-board the *Hinode* spacecraft has been interpreted as heating which causes the singly ionised calcium to become at least doubly ionised. This subject received further excitement when De Pontieu *et al.* (2011) correlated the SOT Ca II H spicules with their coronal equivalent as seen in 171 Å and 211 Å bandpass images of the *Atmospheric Imaging Assembly* (AIA) on-board *Solar Dynamics Observatory* (SDO). Recently, Madjarska, Vanninathan, and Doyle (2011) analysed three large spicules seen in SOT Ca II H images and concluded that "these spicules although very large and dynamic, are not present in spectral lines formed at temperatures above 300 000 K" observed with the *Extreme-ultraviolet Imaging Spectrometer* (EIS) on-board *Hinode*. In addition, their preliminary analysis of solar prominences, which have very similar plasma parameters as spicules with respect to temperatures and densities, showed that prominences are seen in the AIA 171 Å images while EIS observations for one of these prominences revealed an emission not higher than 400 000 K (Fe VIII, $\log T\ (K)\ \sim\ 5.6$). The authors suggested, therefore, that the recent observations of spicules by De Pontieu *et al.* (2011) in AIA/SDO 171 Å and 211 Å channels may come from the existence of transition region emission in these passbands.

The AIA (Lemen *et al.*, 2012) on-board SDO (Pesnell, Thompson, and Chamberlin, 2012) has revolutionised our view of the Sun with its unprecedented cadence, high spatial resolution and large field-of-view. AIA has 10 passbands which cover a wide range of temperatures thus enabling the study of the solar atmosphere from the chromosphere to the corona. Unfortunately, due to the relatively large spectral widths of the AIA passbands, the resultant images are not spectrally pure. Although the emission from these filters are dominated by the intended primary ion, initial analysis show that the contribution from several adjacent spectral lines cannot be ruled out (O'Dwyer *et al.*, 2010). For their analysis they used typical Differential Emission Measure (DEM) distributions for a coronal hole, quiet Sun, active region and flaring plasma. By forward modeling the emission in the AIA filters, Martínez-Sykora *et al.* (2011) concluded that the 131Å, 171 Å and 304 Å passbands have a negligible contribution from the non-dominant ions. The authors used 3D MHD numerical simulations of the solar atmosphere for regions representing "coronal hole, and quiet Sun with hot emerging regions and with hot corona" to calculate the intensity (using CHIANTI)

of spectral lines within the AIA passbands, and investigate the importance of non-dominant lines for the various solar coronal conditions. Important issues related to the AIA passbands have been highlighted recently such as the presence of unidentified transition region and coronal lines in the 211 Å channel (Del Zanna, O'Dwyer, and Mason, 2011). From their study of active region loop footpoints they also suggest that since the 171 Å channel has a significant contribution from cool plasma ($\log T\ (K)\ <\ 5.7$), observations in this channel should be treated with extreme caution.

Similar studies have been conducted for some of the earlier observations by Brooks and Warren (2006) where they investigated the response functions for the 171 Å and 195 Å channels of *Extreme-ultraviolet Imaging Telescope* (EIT) on-board the *Solar and Heliospheric Observatory* (SoHO) and the *Transition Region and Coronal Explorer* (TRACE) using coordinated *Coronal Diagnostic Spectrometer* (CDS) observations of the quiet Sun. The TRACE response functions were also studied by Del Zanna and Mason (2003) and Cirtain (2005) for active regions and flares, respectively.

The overview given above shows that until now there has been no attempt made to understand the thermal response of the filters on different telescopes to spicule observations. The time is now ripe to study this problem as the current high spatial and time resolution observations make it possible to look at features like spicules, bright points, prominences *etc.* in great detail. In the present paper we aim to obtain for the first time a DEM distribution to study the thermal properties of emission registered through the AIA 171 Å passband during off-limb activity above a coronal hole, dominated by spicules. The results obtained here could be applied to observations of any phenomenon with emission at chromospheric and/or transition region temperatures with the 171 Å channel of AIA/SDO. The data used here are described in Section 2. The DEM analysis is given in Section 3. In Section 4 we describe and discuss our results, and in Section 5 we state our conclusions.

## 2. Observations

The *Solar Ultraviolet Measurements of Emitted Radiation* (SUMER; Wilhelm *et al.*, 1995) instrument on-board SoHO (Domingo, Fleck, and Poland, 1995) is a telescope and a spectrometer which uses two detectors to cover a large spectral range from 465 Å to 1610 Å. While detector A is sensitive to wavelengths 780 Å to 1610 Å, detector B works from 660 Å to 1500 Å. From the SUMER archive we selected suitable data which will enable us to study transient events like spicules. The data were taken on 13 June 1998 in and above a coronal hole at the North Pole. Coronal hole off-limb data are the most suitable for this study as the dominant features observed there are spicules. Rouppe van der Voort *et al.* (2009) calculated that there are between 1.5 and 3 Ca II H type II spicules per linear arcsec along the limb in a coronal hole. Hence, our off-limb region of study is intermixed with both type I and type II spicules. In Figure 1 we show context images in Fe IX 171 Å (top, left) and He II 304 Å (bottom, left) taken with the EIT with the position of the SUMER slit over-plotted. We also show

in the Appendix, Figure 6, a comparison between EIT and AIA 304 Å images in order to demonstrate that we are able to determine with EIT images various phenomena in coronal holes off-limb data, e.g. spicules and bright points, despite the instrumental limitations.

In Figure 1, we also show examples of the SUMER spectral data (top/bottom, right) taken co-temporally with the EIT images. We used these images to verify that the emission under the SUMER slit comes only from spicular material and no other features like, for instance, coronal bright points, are present. The spectra were recorded on detector B with a slit of $0.3'' \times 120''$ and 300 s exposure time. The SUMER data reduction was done with the standard software. The spectral lines were identified with the help of the SUMER spectral atlas (Curdt *et al.*, 2001). A list of all the lines used, their corresponding formation temperatures and radiances are given in Table 1. We selected all lines with formation temperatures between $\log T\ (K) = 4.1$ and $\log T\ (K) = 5.8$ which have a sufficient signal-to-noise ratio (above 10). The Ne VIII line was chosen as the upper limit since it is the best SUMER line which has high formation temperature ($\log T\ (K) = 5.8$) close to the formation temperature of Fe IX. All other SUMER lines with higher formation temperatures have in general very poor signal-to-noise ratio. Furthermore, from the analysis of Madjarska, Vanninathan, and Doyle (2011) we know that spicules do not have any signal at temperatures higher than 0.3 MK which makes the use of only SUMER data for this study a reasonable approach. The alignment of the SUMER slit with the EIT images was done by first selecting spectral lines in the SUMER data which have similar formation temperatures as the EIT channels (Fe IX and He II) and then by comparing them.

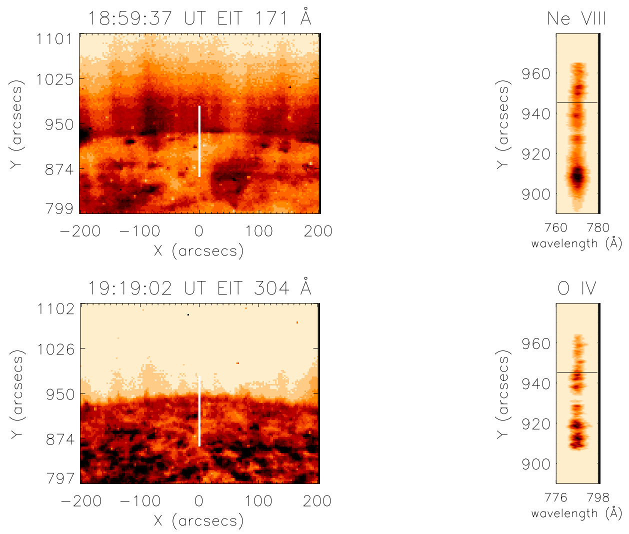


**Figure 1. Top left**: EIT Fe IX/X 171 Å context image with the SUMER slit over-plotted. **Bottom left**: EIT 304 Å image of the same region showing spicular emission. The plotted solid line represents the position of the SUMER slit. **Top right**: Ne VIII 770.42 Å emission along the SUMER slit taken at 19:02:36 UT. **Bottom right**: O IV 787.72 Å along the SUMER slit taken at 19:02:36 UT. The horizontal line in both images denotes the limb position.

**Table 1.** Details of the SUMER spectral lines used for the construction of the DEM

| Wavelength (Å) | Ion | log $T_{max}$ $(K)$ | Radiance $\times 10^3$ $(ergs\ cm^{-2} s^{-1} sr^{-1})$ |
|---|---|---|---|
| 765.150 | N IV | 5.1 | 10.30 |
| 770.420 | Ne VIII | 5.8 | 6.32 |
| 780.300 | Ne VIII | 5.8 | 3.58 |
| 786.470 | S V | 5.2 | 4.82 |
| 787.720 | O IV | 5.2 | 8.89 |
| 977.030 | C III | 4.8 | 179.98 |
| 1031.93 | O VI | 5.5 | 54.95 |
| 1238.82 | N V | 5.3 | 20.88 |
| 1242.80 | N V | 5.3 | 10.68 |
| 1253.80 | S II | 4.2 | 2.52 |
| 1298.96 | Si III | 4.7 | 3.50 |
| 1334.53 | C II | 4.4 | 155.64 |

In order to obtain the off-limb radiances it is important to accurately determine the position of the solar limb. For this purpose we first selected the part of the SUMER spectrum dominated by continuum emission around 1230 Å and the emission in the C I line at 1252.21 Å (log$T$ $(K)$ $=$ 4.0). A tilt in the orientation of the grating with respect to the detector causes the emission along the SUMER slit to be shifted with the dispersion. This vertical displacement was accounted for by using the program delta_pixel.pro. We cut a further two pixels above the identified limb in order to avoid contamination from disk emission. After having subtracted the background from our data we fitted each spectral line with a single Gaussian to determine the total off-limb flux contribution by that line. The Poisson noise for these radiances were also calculated.

## 3. DEM analysis

A DEM distribution gives information about the plasma distribution as a function of temperature along a given line-of-sight (LOS). A DEM, $\phi(T)$, is defined as

$$\phi(T) = n_e^2 \ \frac{dh}{dT} \tag{1}$$

where $n_e$ is the electron density at position $h$ along the LOS at temperature $T$. For an optically thin line in ionisation equilibrium, the DEM and the observed intensity ($I_{obs}$) are associated to each other by the equation

$$I_{obs} = \int A(x) \ G(N,T) \ \phi(T) \ dT \tag{2}$$

where $A(x)$ is the elemental abundance with respect to hydrogen and $G(N,T)$ is the contribution function for a given spectral line. This relationship can be used to derive the DEM from an observed spectrum (Withbroe, 1975) using inversion techniques.

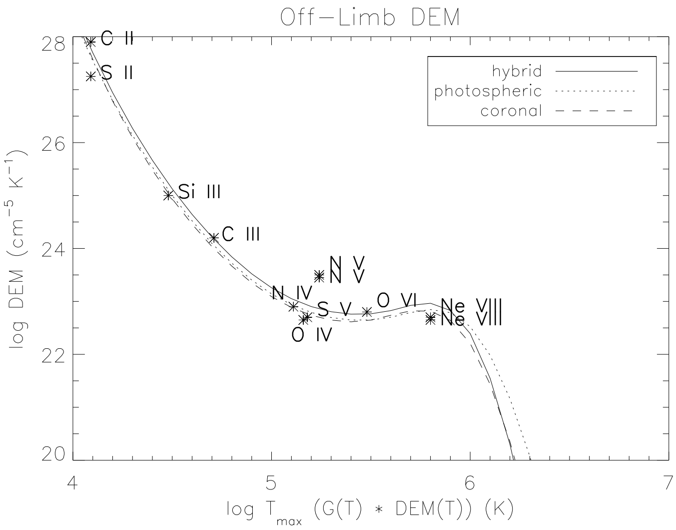


**Figure 2.** The DEM for off-limb data (where spicules are most easily identified) is calculated for different abundances using CHIANTI 6.0.1.

A deconvolution method is used to obtain the DEM from measured spectral intensities. In this paper we use the CHIANTI atomic database version 6.0.1 (Dere *et al.*, 2009). A procedure available along with the CHIANTI package called chianti_dem.pro is used to derive the DEM distribution. This program accepts wavelength, observed intensities and corresponding errors of the spectral lines along with pressure/density and elemental abundances corresponding to the observed region of the Sun as inputs. The best fit for the DEM can be controlled by changing the "mesh points" (an array that specifies the points for the spline that represent the fitted DEM (see CHIANTI: User Guide for further details)).

## 4. Results and Discussion

We have successfully constructed a DEM distribution of spicules for different solar abundances that are predefined in the CHIANTI package (see Figure 2). The derived DEM distribution was used to analyse the thermal response of the AIA 171 Å channel to spicular emission.

In Figure 3 we present the spectral response of the AIA 171 Å channel from our DEM modeling. We found that the radiance in this channel is dominated by emission from the Fe IX 171.07 Å line and has sparingly little contribution from other lines. However, the product of the contribution function and DEM, $G(N,T) \times DEM(T)$ provides a better understanding of the formation

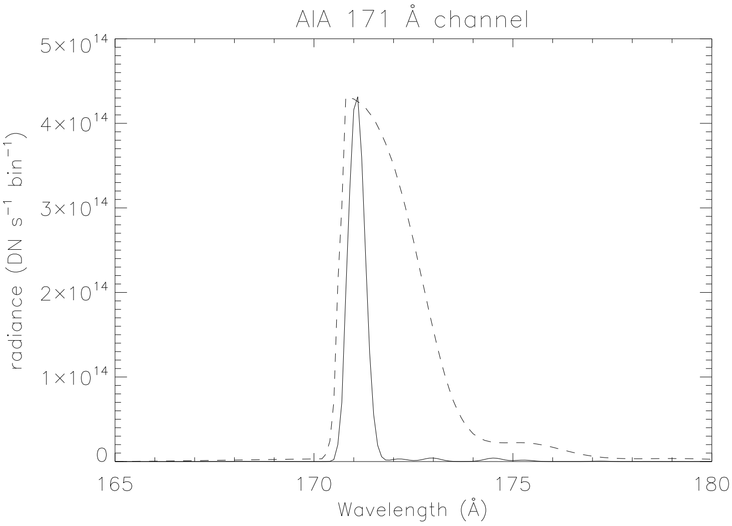


**Figure 3.** The AIA 171 Å passband spectral response from the model DEM (solid line). The wavelength response function of this band is plotted with a dashed line.

temperature of this line for a given phenomenon in the solar atmosphere. This analysis revealed that, although, the contribution function of the Fe IX 171.07 Å line peaks at $\log T_{max}\ (K) = 5.9$ (the solid line in Figure 4(a)), the product $G(N,T) \times DEM(T)$ has its maximum at $\log T_{max}\ (K) = 5.8$ and, therefore, the emission comes from plasma at transition region temperatures. This supports the spectral results of Madjarska, Vanninathan, and Doyle (2011) that spicules may not attain temperatures greater than 300 000 K.

We did a comparative study with prominences since it is known that their plasma properties are similar to that of spicules. As expected the response of the 171 Å line to the prominence DEM from CHIANTI (see Figure 4(b)) showed a significant shift in the emission contribution to $\log T_{max}\ (K) = 5.7$ which is even more pronounced than in the case of spicules. Prominences are visible in the 171 Å passband of AIA but from Figure 4(b) we see that the contribution from million degree plasma is very insignificant.

We then made a similar plot using the quiet Sun DEM from CHIANTI (see Figure 4(c)) and found very contrasting results. The peaks of the line contribution function and the product $G(N,T) \times DEM(T)$ coincide here, unlike the case with the off-limb DEM and prominence DEM. The differences between the three DEMs strongly influence the obtained results. We suggest that a quiet Sun DEM could be affected by emission from plasma at widely differing temperatures as it could originate from numerous sources like loops, coronal bright points, spicules, filaments etc. in an average quiet Sun region.

From the graphs in Figure 4 we were able to numerically integrate the values to obtain what percent of plasma seen in the 171 Å filter is above million degrees. We find that in the case of spicule or prominence observations the contribution is only 3.6% and 0.9%, respectively, whereas for the quiet Sun it is a little over 15%.

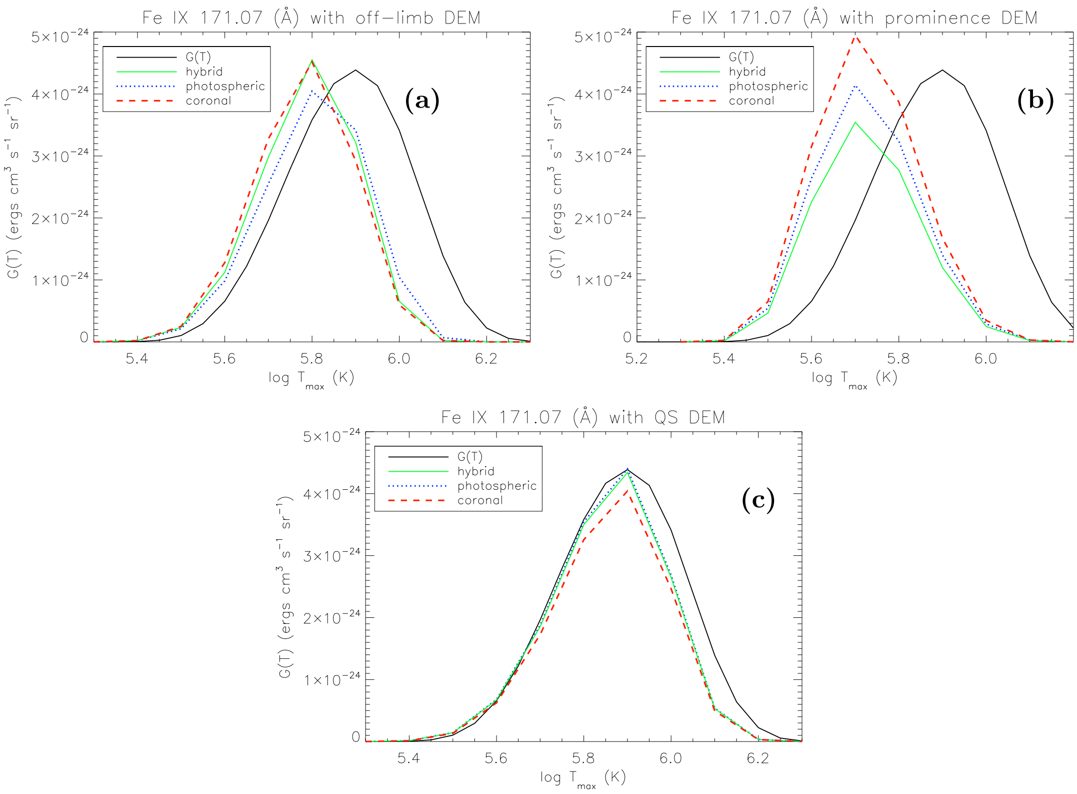


**Figure 4.** The contribution function $G(N,T)$ for Fe IX 171.07 Å (black, solid line) is plotted along with the normalised product $G(N,T) \times DEM(T)$ for three different DEMs (a) off-limb, (b) prominence and (c) quiet Sun and for different solar abundances as indicated in the legend.

We then obtained the line emission flux as a function of temperature. Using CHIANTI we calculated the line emissivity as a function of temperature and then folded it with the QS, prominence and our off-limb DEM distributions. Here again we find discrepancies for the three DEMs used as shown in Figure 5. While the emission of Fe IX 171.07 Å in response to the off-limb DEM peaks at $\log T_{max}\ (K) = 5.8$ (transition region temperature) and that of the prominence DEM is much lower at $\log T_{max}\ (K) = 5.6$, we find that the maximum flux using the quiet Sun DEM occurs at $\log T_{max}\ (K) = 6.0$ (coronal temperature). Since these differences exist in the use of the Fe IX 171.07 Å line, results pertaining to observations in this line can easily be misrepresented.

The sensitivity of some spectral lines to different DEM has previously been demonstrated by Brooks, Warren, and Young (2011). The authors investigated spectroheliograms of active region fan loops produced from Fe VIII and Si VII lines. They found striking similarities in the appearance of the fan loops despite their different formation temperature, $\log T\ (K) = 5.6$ and 5.8 respectively. Note that Fe VIII is the main contributor to the AIA 131 Å channel. It has been found that the Fe VIII 185.213 Å line is particularly sensitive to the slope of the DEM,

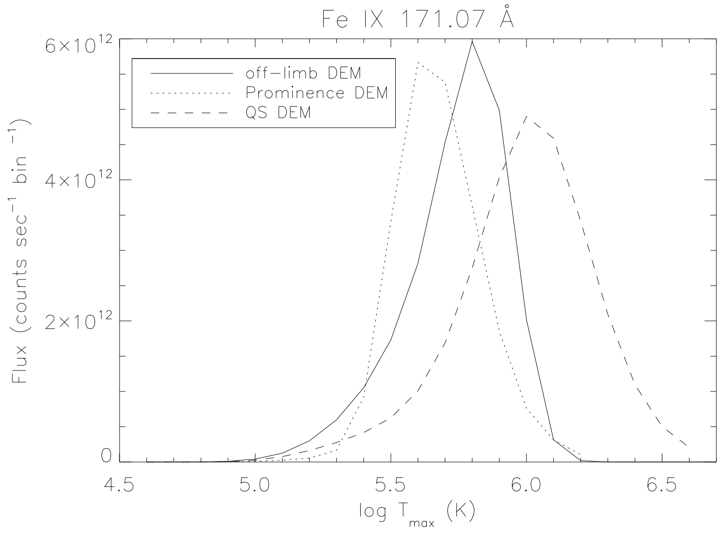


**Figure 5.** A comparison of the Fe IX 171.07 Å line flux as a function of temperature using both off-limb DEM (solid line), quiet Sun DEM (dashed line) and prominence DEM (dotted line)

leading to disproportionate changes in its effective formation temperature. This is similar to the behaviour of the Fe IX line studied here and its impact to the temperature response of the AIA 171 Å channel.

## 5. Conclusions

The aim of the present study was to derive a DEM distribution for a region dominated by spicular emission, best described by an off-limb environment above a coronal hole. Until now spicular studies have always been spoken about in context to the quiet Sun. However, in this paper using spicular, prominence and quiet-Sun DEM distributions, we demonstrated that there is an obvious difference in how the Fe IX 171.07 Å emission changes in these regions. From the off-limb DEM we find that during spicule observations the bulk emission in the AIA 171 Å filter is from cool plasma at $\log T\ (K) = 5.8$ to as low as $\log T\ (K) = 5.5$ with only 3.6% of the plasma being above a million degrees. A similar deduction was made in regard to prominence observations using this filter where the filter is receptive to emission at $\log T\ (K) = 5.7$ to as low as $\log T\ (K) = 5.5$ with a meager 0.8% being over million degrees. Whereas for a quiet Sun region there is significant emission from plasma at $\log T\ (K) = 5.9$ to $\log T\ (K) = 5.55$ with over 15% being above million degrees. From our study we find that the temperature sensitivity of this filter depends on the kind of feature that is observed. Although the Fe IX line can be formed or has a contribution from plasma at million degree temperature, our results suggest that spicule observations in this filter cannot be used as a conclusive evidence that

these phenomena are heated to coronal temperatures. We, therefore, emphasise that future studies related to off-limb features, especially spicules, should adopt the use of the off-limb DEM. We propose that the quiet Sun can be dominated by plasma from neighbouring structures (e.g. loops *etc.*) and this could give rise to the differences that we point out here.

Our results are in agreement with the conclusions made by Del Zanna, O'Dwyer, and Mason (2011) where they use data from active region loops to investigate spectral line contribution to the EUV AIA channels. The outcome of our work shows that mostly transition region emission is registered through the AIA 171 Å channel during observations of certain phenomena like spicules and prominences. We need to further explore the issue raised here and have a better understanding of the thermal characteristics of the observed phenomenon in order to be able to completely and truthfully exploit the state-of-the-art AIA instrument.

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## Appendix

As mentioned in Section 2, coronal hole off-limb data are dominated by spicules. We use EIT images (see Figure 1) to ensure that no coronal bright points are present in the SUMER field-of-view since EIT was the only available imager at the time the SUMER reference spectra were obtained. However, the EIT images do not distinctly reveal spicular structure due to some instrumental limitations: low spatial resolution and high stray-light contribution. In order to establish what we see in the EIT image we compare it with co-temporal AIA 304 Å image (see Figure 6) which has a better spatial resolution. While the off-limb EIT image shows blurred streaks merging together due to its low spatial resolution, the AIA image reveals numerous narrow spikes, i.e. spicules, confirming the abundance of spicules in off-limb coronal hole data.

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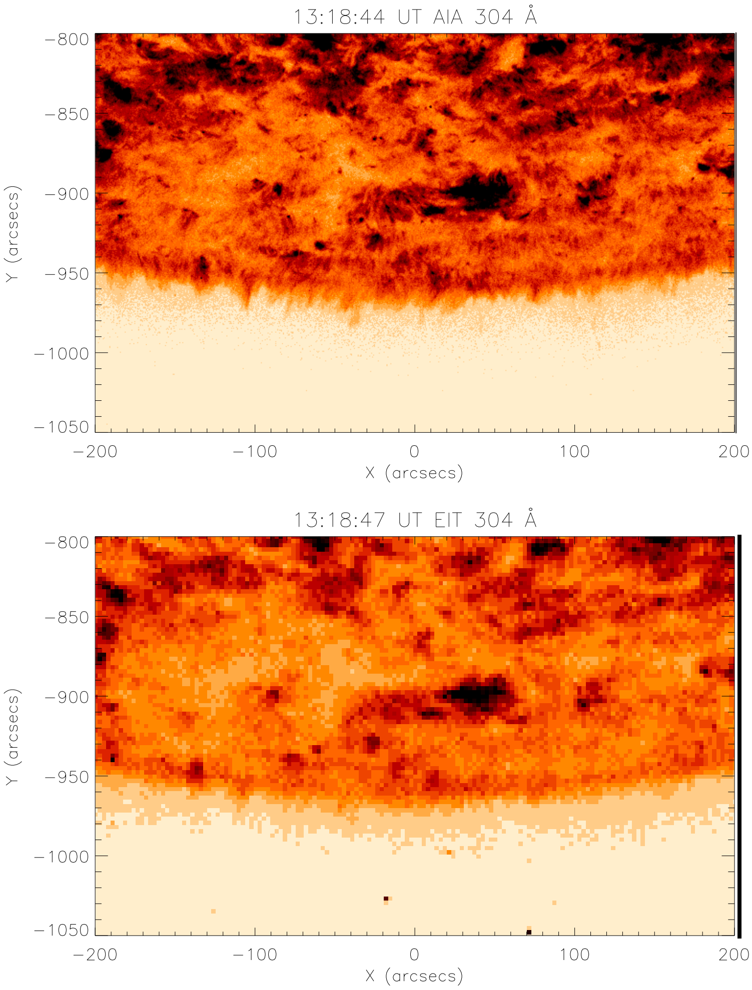


**Figure 6.** AIA 304 Å (top) and EIT 304 Å (bottom) images (colour table reversed) of a coronal hole region at the South Pole taken on 14 May 2010.

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